Novel Epitaxial Growth Technologies for Long-Wavelength (1.1-1.5 μm) Vertical-Cavity Surface-Emitting Lasers and Optical Switches for High-Performance Optical Information Networks

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The goal of this research program is to develop novel techniques for the epitaxial growth and fabrication of vertical-cavity surface-emitting laser structures with lasing wavelengths in the 1.1-1.5 micron regime. Special emphasis will be on the realization of 1300 nm VCSELs and monolithic VCSEL arrays that are useful for the parallel optical data links that will interconnect future computer networks, whose nodes may be distributed across a wide range of distances and are interconnected by optical fibers. The 1300nm VCSELs will provide improved fiber transmission performace as well as a more unified technology platform for the different levels of the interconnection heirarchy. One goal is to design and demonstrate a practical 1300nm VCSEL structure that can be grown by a single epitaxial growth on a convention, hjigh quality GaAs substrate. These structures will use InGaAsN quantum wells, as well as GaAs/AlAs distributed Bragg reflector (DBR) mirrors with a large index difference, which reduces the total thickness to a tract-able level that makes a single-growth approach possible. In this program, we will develop an optimum device design for the fabrication of these VCSEL structures, and we will integrate them into monolithic arrays. We will evaluate the performance of the VCSELs in parallel optical links as well as in VCSEL-based optical switching networks.

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1. Statement of Work (SOW):

The goal of this two-year research program is to develop a novel technology for the epitaxial growth and fabrication of vertical-cavity surface-emitting laser structures with lasing wavelengths in the 1.1 μm to 1.5 μm regime. Special emphasis will be on the realization of 1300 nm VCSELs and monolithic VCSEL arrays, which are useful for the parallel optical data links that will interconnect future computer networks, whose nodes may be distributed across a wide range of distances and are interconnected by optical fibers. The use 1300 nm VCSELs will provide improved fiber transmission performance as well as a more unified technology platform for the different levels of the interconnection hierarchy. We will design and demonstrate a practical 1300 nm VCSEL structure that can be grown by conventional growth techniques on a ternary InGaAs substrate. These structures will contain a GRINSCH active region with one or more strain-compensated InGaAs quantum wells, as well as InGaAs/InAlAs distributed Bragg reflector (DBR) mirrors with a large index difference, which allows the total thickness of each mirror to be reduced, thus making the growth of the complete VCSEL tractable. We will develop an optimum device design for the fabrication of these VCSEL structures, and we will integrate them into monolithic arrays. We will evaluate the performance of these VCSELs in parallel optical links as well as in VCSEL-based optical switching networks. The lasing wavelengths of each array will also be graded using specialized growth techniques that will be developed, which will have important potential applications in wavelength-multiplexed or wavelength-switched optical information networks.

2. Research Program Summary:

The goal of this two-year research program is to develop novel technologies for the epitaxial growth and fabrication of vertical-cavity surface-emitting laser structures with lasing wavelengths in the 1.1 μm to 1.5 μm regime. Special emphasis will be on the realization of 1300 nm VCSELs and monolithic VCSEL arrays that are useful for the parallel optical data links that will interconnect future computer networks, whose nodes may be distributed across a wide range of distances and are interconnected by optical fibers. The use 1300 nm VCSELs will provide improved fiber transmission performance as well as a more unified technology platform for the different levels of the interconnection hierarchy. One goal is to design and demonstrate a practical 1300 nm VCSEL structure that can be grown by a single epitaxial growth on a conventional, high quality GaAs substrate. These structures will use InGaAsN quantum wells, as well as GaAs/AlAs distributed Bragg reflector (DBR) mirrors with a large index difference, which reduces the total thickness to a tractable level that makes a single-growth approach possible. In this program, we will develop an optimum device design for the fabrication of these VCSEL structures, and we will integrate them into monolithic arrays. We will evaluate the performance of these VCSELs in parallel optical links as well as in VCSEL-based optical switching networks.

3. Epitaxial Approach:

VCSELs that emit at longer wavelengths have also been demonstrated using highly-complex, multiple-growth technologies, such as wafer-fusion (1.3 and 1.5 μm VCSELs), or the use of compliant substrates, whose manufacturability and reliability

remain in doubt. A single-growth approach would be the ideal solution to the long-wavelength VCSEL problem. *At present, there is no all-epitaxially-grown long wavelength VCSEL technology*, nor is there any other approach with proven performance or reliability. Long-wavelength operation using a single-growth epitaxial VCSEL structure grown on a GaAs substrate has not yet been demonstrated due to the inherent problem of a large lattice mismatch (ε>2.5%) between the $In_xGa_{1-x}As$ ($x>0.4$) active layer and the GaAs substrate. The growth of a highly-strained VCSEL structure on a ternary substrate represents a promising single-growth approach, but the broad availability of these substrates in the future is unknown. To solve this problem, we propose a new single-growth epitaxial approach that requires only conventional GaAs substrates and uses only conventional GaAs VCSEL processing technology.

This new approach uses a novel narrow-bandgap material, InGaAsN, lattice-matched to GaAs - as the active region, while preserving the larger index difference of the conventional AlGaAs/AlAs DBRs. It offers a structural simplicity that makes VCSELs far easier to fabricate than approaches that require the wafer bonding of one or more GaAs/AlGaAs DBRs to an InGaAsP/InP active region. The objective of this research is to investigate the use of such a strain-free material family, $In_xGa_{1-x}As_{1-y}N_y$, to achieve 1.3 μm VCSEL operation on a GaAs substrate. We will develop a practical and potentially manufacturable new VCSEL technology that is based on a single-growth using conventional growth systems, using only conventional substrates and established device fabrication techniques.

4. Long Wavelength 1.3 μm VCSELs using $In_xGa_{1-x}As_{1-y}N_y$ active layers grown on GaAs Substrates

Fig. 1 shows the bandgap energy as a function of lattice constant for a variety of III-V compound semiconductor materials. Due to the large electronegativity of nitrogen atoms, a negative bandgap energy has been predicted for N-containing compounds such as $GaAs_{1-x}N_x$, $GaP_{1-x}N_x$, and $AlAs_{1-x}N_x$. This huge bowing of bandgap energy provides another degree of freedom in bandgap engineering by providing novel material systems that can be exploited to realize long-wavelength lasers or other electronic devices on GaAs substrates. For example, adding 10% In to GaAs increases the lattice constant of the $In_{0.1}Ga_{0.9}As$ layer, placing it under compressive strain, while adding approximately 2% N to the $In_{0.1}Ga_{0.9}As$ layer decreases its lattice constant and thus compensates for the compressive strain. Thus a strain-free material, $In_xGa_{1-x}As_{1-y}N_y$ grown on GaAs, can be easily obtained by choosing suitable compositions x and y. Furthermore, due to this unique bandgap bowing effect, the bandgap energy of $In_xGa_{1-x}As_{1-y}N_y$ can be significantly reduced below that of GaAs. This result strongly suggests that the $In_xGa_{1-x}As_{1-y}N_y$ alloy has a great potential for long-wavelength laser applications.

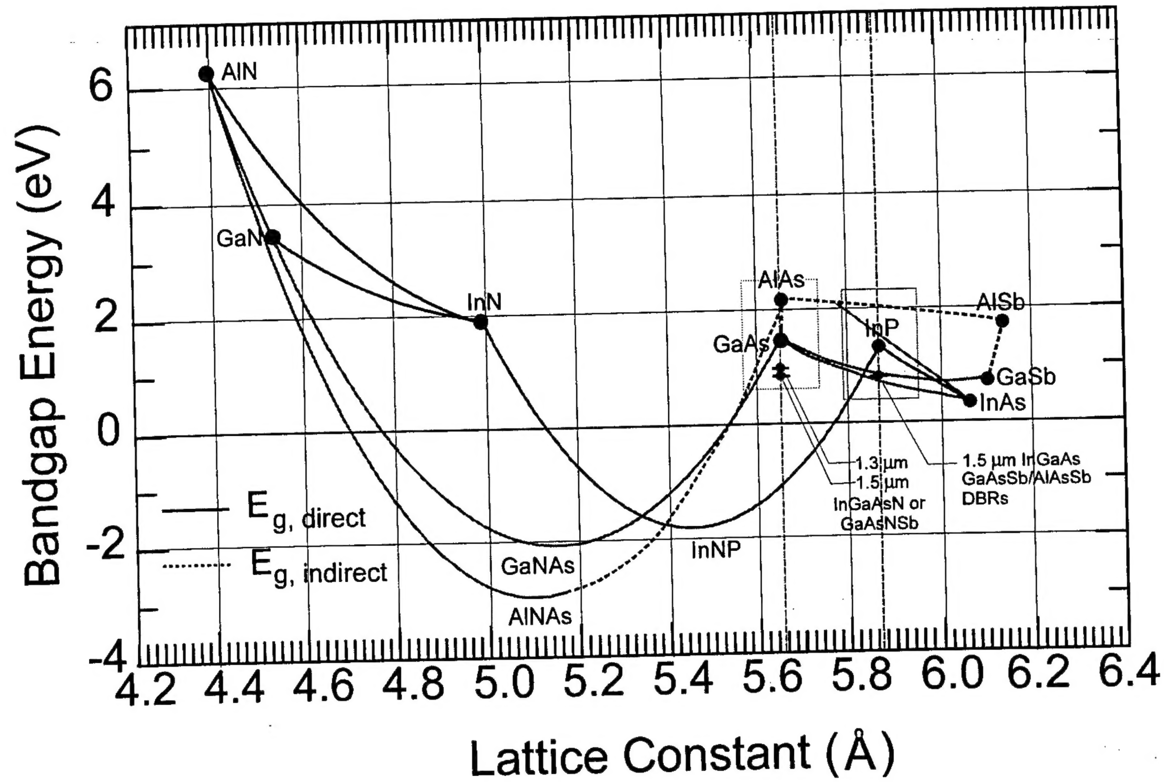

Fig. 1 The composition dependence of the bandgap energies of III-NAs and III-NP alloys calculated based on the Van Vechten model. The boxes indicate two different material systems that can be used to achieve long wavelength VCSELs.

5. Pulsed Lasing of Multi-Quantum Well GaInNAs/GaAs Lasers with Low Threshold Current Density Grown by MOCVD

The $Ga_{1-x}In_xN_yAs_{1-y}$/GaAs material system represents a promising approach for achieving long wavelength semiconductor lasers with a large characteristics temperature (T_o) as well as VCSELs on a high-quality GaAs substrate. For VCSELs, this epitaxial approach takes advantage of the large index difference of GaAs/AlAs DBR mirrors (thus smaller growth thickness), as well as the established processing technology of AlGaAs/GaAs VCSELs. Pulsed lasing of edge-emitting $Ga_{1-x}In_xN_yAs_{1-y}$/GaAs quantum well (QW) lasers has previously been achieved at 1.18 μm and at 1.31 μm at room temperature using material grown by gas source MBE [1], with a threshold current as low as 1.4 kA/cm^2. However, the progress in MOCVD-grown GaInNAs/GaAs material has lagged behind, and the best result to date was achieved by a 2-QW laser under pulsed lasing conditions [2], with a lasing wavelength of ~1.18 μm and a threshold current density of 3.37 kA/cm^2. This paper reports a signficant improvement in the performance of MOCVD-grown $Ga_{1-x}In_xN_yAs_{1-y}$/GaAs lasers. Using a new MOCVD regrowth technique [3], 3-QW $Ga_{1-x}In_xN_yAs_{1-y}$/GaAs edge-emitting lasers with x=0.3 and y ~ 0.3-0.4 % have been achieved, with lasing wavelengths in the 1.15-1.19 μm regime and threshold current density as low as ~600-700 A/cm^2, which is the lowest for any MOCVD-grown devices. Ridge-waveguide lasers as well as planar broad stripe lasers defined by the selective lateral wet oxidation of an $Al_{0.98}Ga_{0.02}As$ layer have been fabricated.

The GaInNAs lasers were grown in an IR-heated, horizontal flow OMVPE reactor on N+ GaAs substrates oriented at 6° off (100) towards <111>A. The $In_{0.3}Ga_{0.7}As_{0.997}N_{0.003}$/GaAs QWs were grown at 535°C using trimethylindium, trimethylgallium, 100% arsine, and dimethylhydrazine (DMHy). Diethyltellurium and carbon tetrachloride were used as Te-doping and C-doping precursors, respectively. The growth rate of the $In_{0.3}Ga_{0.7}As_{0.995}N_{0.005}$ and GaAs layers were 5.4, and 8 Å/sec, respectively, and the ratio of [DMHy]/([DMHy]+[AsH_3]) was fixed at 0.6. To eliminate the Te memory effect [3] that reduced the radiative efficiency of the GaInNAs/GaAs MQWs, in-situ cleaning the quartz reactor and graphite susceptor with hydrogen chloride at 830°C were employed prior to the regrowth of the MQW active region and the p-cladding layer.

Pulsed lasing has been achieved at room temperature by edge-emitting GaInNAs/GaAs lasers with 3 QWs (7 nm wells separated by 10 nm barriers), $Al_{0.3}Ga_{0.7}As$ cladding layers, a cavity length of 1000 μm and a stripe width W that varyies from 2 μm to 60 μm. The light-vs-current characteristic and lasing spectrum of a device with W= 60 μm are shown in fig. 2, with a threshold current of 350 mA and a current density of ~635 A/cm^2, and a lasing wavelength of ~1.165 μm at 1.0 A. The temperature dependence of the threshold current for these devices show a characteristic temperature of T_o= 125 K -133 K. The longest lasing wavelength achieved was ~1200 nm. The dependence of the lasing characteristics on W has been obtained. Figure 3 shows the characteristics of a laser with W=25 μm, which was defined by the selective wet oxidation of an $Al_{0.98}Ga_{0.02}As$ layer. The device has a threshold current of 245 mA and a threshold current density of 950 A/cm^2, with a lasing wavelength of ~1.16 μm.

[1] M. Kondow, et al., IEEE J. Quantum electronics, Vol. 3, pp.719-730, 1997.
[2] S. Sato, S. Satoh, Electron. Lett., Vol. 34, no. 15, pp. 1495-1497, 1998.
[3] N. Y. Li, C. P. Hains, K. Yang, and J. Cheng, submitted to Appl. Phys. Lett., 1999.

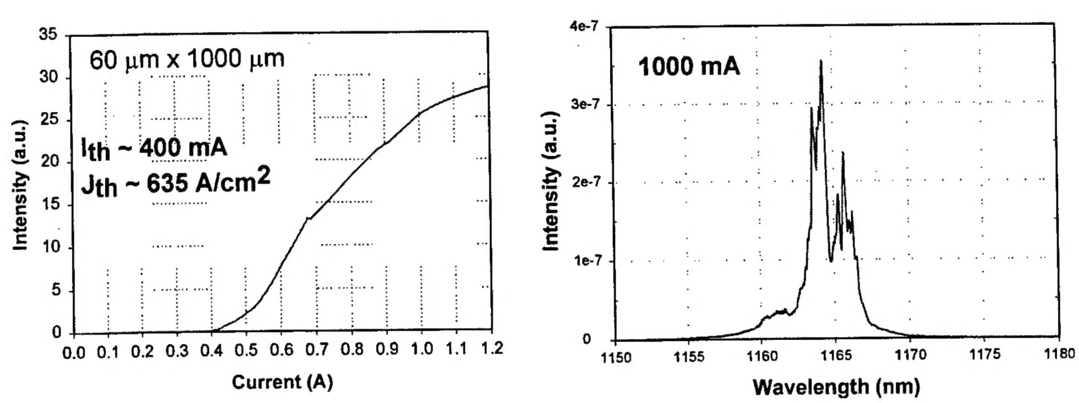

Figure 2. The pulsed lasing characteristic and lasing spectrum of a 3-QW GaInNAs/GaAs laser with W=60 μm at 300 K.

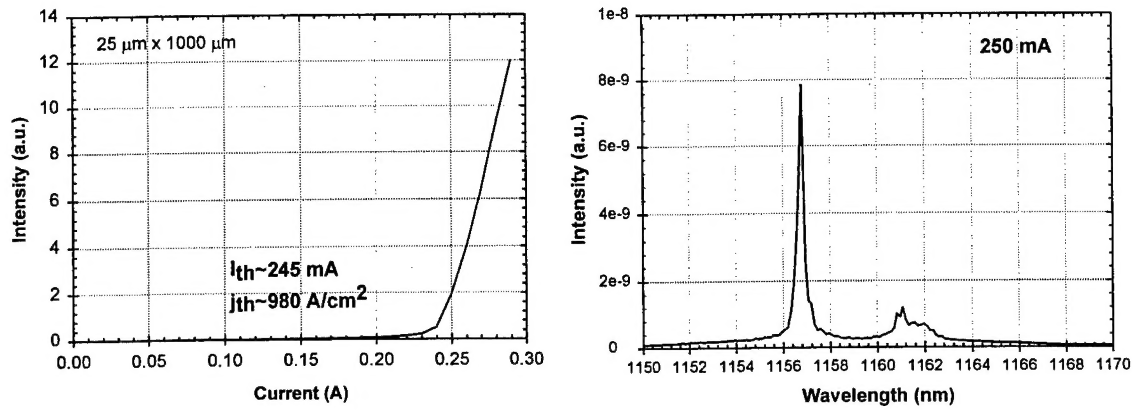

Figure 3. The pulsed light-vs-current characteristic and lasing spectrum of a 3-QW GaInNAs/GaAs laser at 300 K, with W = 25 μm defined by the selective lateral oxidation of an $Al_{0.98}Ga_{0.02}As$ layer.